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Existence of Dust Atoms & Modified OML Theory

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Abstract. Based on adiabatic model and nonlinear screening of the dust grains immersed in electron-ion plasma, an important relation is obtained between the maximum potential (and therefore the charge) of the dust grain and the temperature of the electrons. A Thomas- Fermi equation suggesting the existence of dust atom with a well-defined atomic radius is also derived. Briefly a new approach for obtaining floating potential has been introduced. This novel approach is valid for those cases when the standard OML theory is not applicable

We know that for an ideal gas, with constant specific heat, the total entropy S_e+S_i is conserved, from which immediately follows the Poisson adiabatic relations i.e., $T^{3/2}/n$=const and $P/n^{5/3}$=const. Considering nonlinear screening of isolated dust grains in a plasma, we assume that the electrons and ions are inertialess and that the dust grains are immobile. Thus we can write from the momentum equation of electrons and ions

$$\frac{n_e}{n_{oe}} = \left(1-\frac{2}{5}\frac{e\,|\varphi|}{T_{oe}}\right)^{3/2};\ \frac{n_i}{n_{oi}} = \left(1+\frac{2}{5}Z_i\frac{e\,|\varphi|}{T_{oi}}\right)^{3/2} \qquad (1)$$

The Poisson equation is given as $\nabla^2|\varphi| = 4\pi e\,(Z_i n_i - n_e)$.The electrons having lesser thermal energies cannot penetrate into the potential barrier of the dust grain. This scenario is well described by the expression (1) of the electron density, from which follows the maximum potential field to be $|\varphi|_{Max} = 5/2T_{oe}(ev)/e^2$. On the other hand, the potential field becomes maximum only on the surface of dust grain, i.e., $|\varphi|_{Max} = Z_D e/r_D$

Combining last two relations, we obtain a very important relation between the charge number and the temperature, for a given radius of the dust grain,

$$Z_D = 2.5\frac{T_{oe}}{e^2}r_D \qquad (2)$$

where r_D is the radius of the dust grain. This simple relation (2) exactly defines the surface charge of the dust grain and is valid as long as the mean distance between dust grains is larger than the Debye length.

Table: Some typical Plasmas

Environment	**T_e (eV)**	**r_D (μm)**	**Z_d**	**r_o/λ_D**
Zodial dust disk (1AU)	10	10	5	1×10^5
Solar F-corona	80	0.3	1	3×10^4
Planetary Nebulae (em)	1	0.2	30	3×10^2
Rocket Exhausts (near ground)	0.3	0.5	2	2×10^2
Halley's Comet				
Inside Ionopause	<0.1	0.1-10	>1	$10\text{-}10^3$
Outside Ionopause	1	0.01-10	>10	$10\text{-}10^4$

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Using different values of the T_e and r_D we calculated the magnitude of the charge Z_D from (2) for various plasma environments and found it to be in good agreement with the values cited in the Mendis table[1] and Table I given above.

Now we consider the Thomas-Fermi model for the dust grains. In the electron-proton plasma, in the vicinity of the grains, Eq. (1) allows us to write the Poisson equation for vanishingly small n_e. Introducing dimensionless quantities, we obtain the Thomas-Fermi-type of equation

$$\nabla^2\Phi = (1+\Phi)^{3/2} \tag{3}$$

Where $\Phi = 2Z_i e/5T_i\,|\varphi|$. It may be noted that our derivation of the Eq.(3) is analogous to that of Thomas-Fermi Model and here energies of the ionization, excitation, and thermal motion of electrons are not separately calculated; these automatically enter in the total energy of protons. To present a simple picture of the motion of protons around the dust grain, we suppose that $T_i = T_e$ and that in the r.h.s. of the Eq.(3) $\Phi \cong 1(n_e \to 0)$, which means that we are considering protons which are very close to the dust grains, thus we obtain $\nabla^2\Phi = 2^{3/2}$. Consequently, we obtain expression for the protons potential energy in the form

$$U_i = \frac{1}{2} m_i \omega_{pi}^2\, r^2 \tag{4}$$

Eq. (4) shows that the protons are acting like Harmonic Oscillators. *O*scillation length of the proton which in our case m_i=m_p is of the order of 10^{-3} cm. This shows that the protons are oscillating in the vicinity of dust grain at a distance larger than the dust grain size. We therefore conclude that the existence of such gigantic atoms is indeed a possibility. From the motion of a particle in an external field we find the radius of the proton in the last shell far from the grain surface will be $r_{last} = r_{Z_D} - r_D = Z_D\hbar^2/2m_e e^2$[2]. Evidently the distance r_{last}<< Debye length.

We know the well-known OML result that φ_f (floating potential) is solution of [3]

$$\left(\frac{T_e}{m_e}\right)^{1/2} \exp\left(-\frac{e|\varphi_f|}{K_B T_e}\right) = \left(\frac{T_i}{m_i}\right)^{1/2}\left(1+\frac{e|\varphi_f|}{K_B T_i}\right) \tag{5}$$

Above equation seems not to be general as it is always useful to consider a specific situation, for example when $e|\varphi_f| > K_B T_e$ and on the other hand when the object is removed from a plasma i.e., $\varphi_f = 0$ it becomes invalid. Yet, it yields a good approximation and provides a good description on the surface of the object. Now we obtain another equation using for obtaining the floating potential by including both the current outward from the spherical object and the current coming from infinity is introduced, details can be found in [4]

$$\frac{n_{oe}}{Z_i n_{oi}}\left(\frac{T_e}{m_e}\right)^{1/2}\left[1-\exp\left(-\frac{e|\varphi_f|}{K_B T_e}\right)\right] = \left(\frac{T_i}{m_i}\right)^{1/2}\left(\frac{e|\varphi_f|}{K_B T_i}\right) \tag{6}$$

Above equation (6) also valid for $\varphi_f = 0$. Here a new question arises about the equality since near the surface, there exists collection of ions (plasma near the surface may be inhomogeneous or $Z_i n_i > n_e$.

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